PB-245 741

REPORT ON COOLING TOWERS AND WEATHER TO FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

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Prepared for:

Federal Water Pollution Control

February 1969

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PB 245 741

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February, 1969

by

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Federal Water Pollution Control Administration, Northwest Region
Pacific Northwest Water Laboratory
Corvallis, Oregon

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BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession

4. Title and Subtitle
Report on Cooling Towers & Weather to Federal Water Pollution Control Administration

5. Report Date
Feb. 1969

6.

7. Author(s)
Dr. Fred W. Decker

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Oregon State University
Corvallis, Oregon

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
U.S. Dept. of the Interior
Federal Water Pollution Control Admin.
Pacific Northwest Water Lab.
Corvallis, Oregon

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstracts
The report recounts an investigation into the theory & reports of actual operations of various cooling towers suggesting that in suitable sites the bad effects will not occur. It also suggests the methods for identifying potentially hazardous or nuisance situations so as to avoid selecting them inadvertently for new installations.

17. Key Words and Document Analysis. 17a. Descriptors
* Cooling towers
Fog
* Pollution

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

PRICES SUBJECT TO CHANGE

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 30
i.	20. Security Class (This Page) UNCLASSIFIED	22. Price 3.75-2.25

Library
Environmental Protection Agency
Region VII

PREFACE

The investigation reported herein was undertaken by Dr. Fred W. Decker at the request of the Federal Water Pollution Control Administration. Dr. Decker is Associate Professor of Physics, Oregon State University, and a consultant meteorologist on air pollution and related meterologic problems.

COOLING TOWERS AND WEATHER

Fred W. Decker

SUMMARY

Possible nuisances created by efflux from cooling towers raised questions of fog, precipitation, and esthetic effects on neighboring property usage. Experience in Europe and computation included here showed low probability of fog, while uncertainties concerning precipitation may need resolution to determine certain marginal probabilities of drizzle-caused fog. Esthetic objections have not materialized to any great extent, neither as to the cooling tower structures nor as to their plumes.

This report surveys the various questions raised and concludes that except for extremely poorly located cooling towers the operators should encounter very little if any liability because of nuisance to neighbors. A properly conducted field meteorological survey should obviate all such mistakes.

Corvallis, Oregon
February, 1969

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COOLING TOWERS AND WEATHER

Fred W. Decker, Ph. D.

INTRODUCTION

The fog suggested to result from evaporative cooling has raised great apprehensions among planners considering the use of industrial cooling towers in lieu of once-through cooling. This report recounts an investigation into the theory and reports of actual operations of various cooling towers suggesting that in suitable sites the bad effects will not occur. We also suggest the methods for identifying potentially hazardous or nuisance situations so as to avoid selecting them inadvertently for new installations. We conclude that evaporative cooling towers will operate satisfactorily and that a relative few sites will appear which planners must omit because of unfavorable likely effects on cooling towers in those locations.

However, between the two types of cooling towers, namely the mechanical-draft and the natural-draft types, the tall construction of the natural draft tower confers a distinct advantage apparently because of the assurance that the emissions must enter the atmosphere at a greater height ordinarily than the emissions from a mechanical-draft unit. Even this feature might not remain if mechanical-draft units get equipped with suitable chimneys for high-level emissions or get located on hillsides or other elevated positions.

"Fog" hardly describes the condition accurately in many cases, since writers have tended to assume a fog will appear whenever the efflux of the tower has visible water droplets in it. Actually, this situation may (and

ordinarily does) produce only a visible plume which rises from the orifice of the tower because of the warmer temperature of the air re-entering the ambient after gaining heat and moisture inside the tower. In principle, the emission, whether rendered visible or not, would rise indefinitely in still air. Why, then, should we ever see a report of "fog" at the ground near a cooling tower?

The answer appears probably in the effects of (a) aerodynamic downwash of the airflow in the lee of the tower and neighboring structures or (b) a drizzle precipitation from the plume itself falling into stagnant, humid, chilled air next to the surface. In the latter case the evaporation into the surface layer would form fog. The operating temperatures of cooling towers seem to preclude ever having such a heavy water droplet load in the efflux as to offset the buoyancy of the warmed air and settle by negative buoyancy, so we dismiss this effect of wet-scrubbed exhaust fumes described by Scorer (16, pp. 215-217), an effect more likely to occur in industrial driers.

The problem of aerodynamic downwash more profoundly afflicts the mechanical-draft cooling tower, which ordinarily does not emit at as great heights as the natural-draft tower. Consequently, at certain critical wind speeds and atmospheric stability for a given installation, the emerging plume may get carried downward to the ground surface and can create a nuisance or serious hazard for highways and other works which suffer from impaired visibility.

Pond cooling should provide the greatest chance of fog formation at the surface. This method of cooling involves the release of vapor into the lowest layers, and a stable atmosphere will keep the vapor-laden air trapped next to the surface. Since the pond could have a higher temperature than the air, the vapor would form a "steam fog" in the cooler air.

Low-level plumes from mechanical-draft towers would have the next greatest probability of causing surface fog, while a higher plume from a natural-draft tower would have the least probability.

Precipitation may provide a more subtle effect even when the visible plume appears to travel aloft and to provide no visual obstruction at the ground. A dense water-droplet plume promotes coalescence of the water droplets, and if dilution does not proceed rapidly in the ambient air such a plume can readily precipitate warm water droplets. These falling droplets do not substantially restrict visibility and could easily fall unnoticed into the surface air, evaporating as they fall. The resulting increase in the water vapor content of the surface air, then, coupled with the nocturnal cooling effects which normally precede a fog could assure the arrival of fog conditions earlier than nature would have provided.

This paper seeks to explore objectively those conditions which will produce the undesirable results alleged to occur, to stipulate conditions which planners should avoid in site selection, and to suggest the investigations which will reveal the undesirable situations prior to the actual installation of cooling tower systems.

REPORTED TROUBLES

Downwash has provided the most specific trouble reports of the kind typified in a report by Hall (7). This case involved a gusty west wind carrying the plume from a mechanical-draft tower emitting at low level and washing this plume down over a major expressway some 400 feet from the cooling tower. The ensuing investigation named one other condition in addition to the gusty west wind with low temperature and high humidity as a potential fog-producing situation, namely the stagnant condition with a low-level inversion and moist, cool air.

Other reports in the literature have alluded to the fog problem without specific case details, viz. a report by Buss (3) on means to "control fog from cooling towers" by reducing the relative humidity of the efflux through use of coils for transferring some of the heat to the updraft as sensible heat instead of accomplishing most of the cooling through evaporation from the warm water directly into the air passing through the tower.

Humidity increase thought possible even without the production of fog caused one elaborate investigation in England to rebut the allegation of a fireworks factory owner that the increased humidity caused by the cooling tower would interfere with certain operations of his plant and would harm the materials in storage, particularly the cardboard. The report in 1963 showed that, actually, the instruments experienced significantly less humidity when downwind of the cooling tower, an effect attributed not to the tower itself but to the fact that winds from that direction (east) arrived with lower humidity as they decend from higher terrain to the east of the tower (5).

Precipitation can certainly occur from cooling towers, as witness the light snowfall at Oak Ridge, Tenn., on 22 December 1960, when mechanical-draft cooling towers evidently emitted plumes containing so much supercooled liquid water that the Bergeron process of precipitation occurred (ice crystals growing in an environment of supercooled liquid because of the vapor-pressure difference).

Wind can affect cooling towers not constructed to withstand damage, a problem unique to the large natural-draft units standing 300 ft. tall or higher. However, engineers who have investigated the collapse of the three cooling towers at Ferrybridge, England, during the gale of 1 November 1965 believe they have adequately allowed for future needs of design to avoid recurrence of this disaster (6).

Freezing of the water inside natural-draft units should not occur if proper design factors get included to assure enough concentration of the heat discharge (14).

In seeking information concerning the experience of European cooling-tower operators, I approached the British Meteorological Office for suggestions of those who had experience with weather effects and cooling towers. This led to a series of contacts in Britain and on the Continent in August and September 1968. The summary of these contacts below gives the "state of the art" as reflected in these conversations.

Mr. W. E. Scriven of the Central Electricity Generating Board (CEGB) at Walden House, London, expressed confidence that "eliminators" installed

to collect the droplets swept upward in a natural-draft tower would prevent practically all precipitation, but specific provisions must still be made to avoid "carry-out" as the wind blows at high speed through the lower parts of the tower. He indicated complete confidence that the design features now incorporated to make the towers withstand high winds would succeed. In fact, he said that the CEGB now stands ready to design other towers for a fee incorporating the results of experience such as that gained after the Ferrybridge disaster. (Inquiries should go to W. A. Fitzherbert, General Design Dept., Civil Branch, CEGB, 24 Cathedral Place, London EC4.)

At Leatherhead, Surrey, a conference with Messrs. D. H. Lucas and G. Spurr of the CEGB Laboratories and Planning Dept., respectively, elicited observations that no serious objections had yet appeared concerning the massiveness of the cooling towers, nor had people objected about the long persistent plumes emitted under conditions of high humidity. This might have indicated success of the public education campaign explaining the true nature of the emissions as pure water rather than "fumes". Shading or screening the towers with trees could have the effect of hiding the towers from nearby view while also impeding the strong windflow which would cause "carry-through" when wind rushes across the open space at the bottom of the cooling tower. They also observed that the tall natural-draft units provide the benefit of removal to the region above a low-level inversion or stable layer next to the surface, whereas a mechanical-draft unit might not expell the efflux high enough to surmount the stable layer.

At Paris, M. Jaquet of Electricite' de France (EDF) at Chatou indicated that only recently has much attention turned to cooling by means other than use of streamwater. However, the growth of the demand for industrial cooling has certainly focussed attention on the problems of thermal pollution in streams like the Seine which run slack in the summer. He said that the EDF now has a computer model under construction using measurements made in situ at the power plants. Measurements include radiation, temperature, and wind; both normal and heated evaporation pans provide data on water loss. He had the impression that in Britain the Alkali Inspector has a powerful influence on design, since the inspector requires that planners and designers prove that the visible plumes will not cause chemical pollution. M. Jacquet applauded the success of the efforts of Mr. Lucas, et al., in convincing the British public that whereas the plume from a cooling tower does not constitute pollution, the use of a cooling tower enables generation of electricity which assures fume-free heating by electricity and consequent reduction of pollution.

At Lausanne, I conferred with Mr. R. W. Peter, Chief Engineer of Centrale Thermique de Vouvry S. A. (CTV), who conducted a tour of the remarkable 300 MW power plant he had build on the Chavalon Alp overlooking the Rhone Valley and Lake Geneva. This oil-fired power plant occupies a site 1456 ft above the valley floor east of Lake Geneva with a 394 ft stack emitting any sulfur fumes safely above the stable air which often fills the region at lower levels. The mechanical-draft cooling towers by the firm Balcke of Germany have the benefit of emitting water vapor in a place which has no

neighbors offended by the cloud or fog which might occur at times. Air movement at this elevation above the valley assures dilution and early dissipation of the plume usually, but when it does persist it does not invade regions occupied by people offended at the appearance. The extremely low sulfur content of the air measured in the valley (13) would argue for correspondingly slight, probably undetectable, increase of humidity as the result of the action of the cooling towers, which emit at 1500 ft above the valley floor. This Chavalon site selection had involved meteorological analysis by Lugeon (10) and others.

At London, before returning from Europe, I received a delayed message from Brussels indicating that Solvay had encountered no trouble with fog or carryover from the cooling towers of that chemical firm.

Near London, at Cockfosters, I conferred with Mr. I. Davies of the Southern Project Group, CEGB, who provided copies of reports including the one on the Fireworks Factory humidity investigation mentioned above. He observed that whereas the mechanical-draft towers may involve lower capital costs than natural-draft towers, they cause more carryover to load the eliminators. I would add that this assures a higher chance of substantial precipitation nearby with consequent fog production.

These direct inquiries plus a review of the literature (8, 12) appear to indicate that modern design of natural draft cooling towers successfully coped with problems which earlier had perplexed engineers when downwash or precipitation from droplet-ladded plumes of carryover caused fog nearby or when

blow-through deposited water or ice on terrain near the base structure of a natural-draft tower. The modern solutions appear to exist in the following measures:

1. "Eliminators" which intercept the upward carried droplets in the region above the packing.

2. Wind break or screening to prevent strong winds blowing directly across the bottom of the cooling tower.

3. Site selection to assure an adequate area around the tower in which any precipitation may fall without nuisance, but "exclusion areas" around nuclear power plants probably provide such areas.

4. Site selection to eliminate possible nuisance of the cooling tower (either natural-draft or mechanical-draft) for nearby activities, again a factor probably covered for safety reasons in the case of a nuclear reactor.

Since the engineering design has already apparently solved the problems which construction features in the tower itself can attack, it appears that in this report we should define the meteorological factors which will influence most profoundly the site selection and that we should develop the anticipated performance of a cooling tower in a generalized location.

PHYSICAL PROCESSES

The production of the visible plume and its behavior upon entering the atmosphere deserve scrutiny to determine the effects produced under various kinds of weather likely to occur. If no visible plume occurred, hardly any

"weather effect" appears to develop in the efflux. The presence of that plume seems essential to initiate any of the unfavorable interactions with the atmosphere commonly classified as "weather effects". Lacking liquid droplets (or ice crystals) in the plume, only an increase in vapor content could ensue, and this probably would at worst produce the kind of effect alleged (but not substantiated) in the case of the British cooling tower. The question then arises, how can the visible plume occur, and what are its properties?

Just as the contrail produced by an aircraft emitting water vapor into the atmosphere, the plume from a cooling tower results from the mixing of ambient air with the warm, humid air which has taken heat and vapor from the water cooled in the tower. This mixture probably occurs often, if not generally, inside the tower itself as the ambient air which passed through the tower without contacting the water surface mixes with the parcels of air which have had intimate contact with the water surface. We must assume that even when no carryover occurs to take droplets torn from the liquid water inside the tower the humidified, warmed air parcels will mix with the cooler, unsaturated ambient air inside the tower and may produce visible droplets or "fog", which then passes out the orifice as a visible plume.

The mixing of saturated air masses at two different temperatures will always result in an "apparent temperature" for which the "apparent vapor content" expressed as a mixing ratio exceeds the saturation value. Equilibrium then occurs after some of the water vapor condenses, releasing latent heat and raising the temperature along a condensation curve (1, 2). The

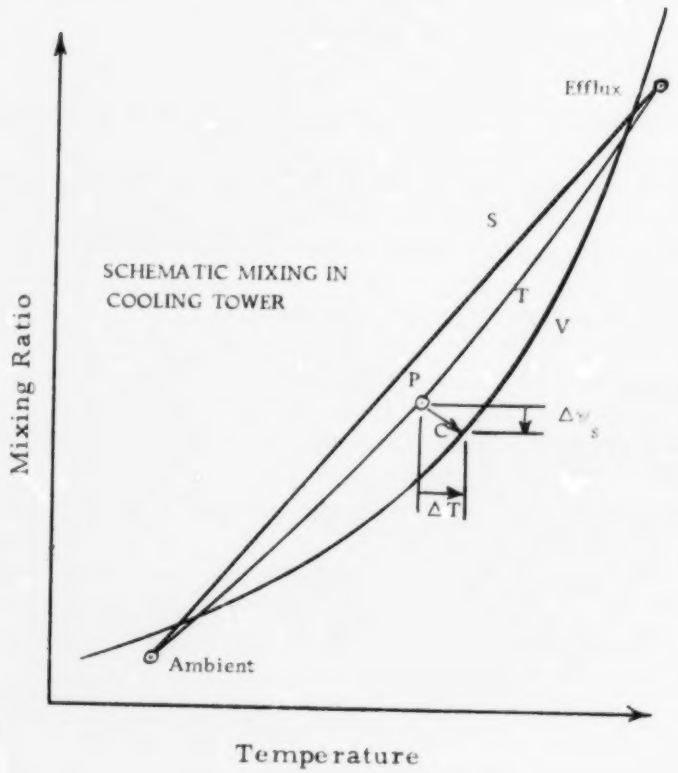
V. Saturated vapor curve.

S. Straight-line approximation.

T. True curve representing various mixing proportions.

P. Result of mixing equal masses of ambient air and efflux before condensation.

C. Condensation curve converting some vapor (Δw_s) to liquid and realizing the corresponding latent heat to raise temperature ΔT.



condensation curve has a slope of about 4 1/2 g/kg decrease in mixing ratio (vapor to dry air) per Centigrade degree rise in temperature in the region of 10°C to 40°C. Thus, the mixed efflux and ambient air will initially have an amount of suspended liquid water which depends upon the position of the "apparent temperature" point relative to the true saturation curve. In order to minimize error, this paper uses the true "apparent temperature" curve (labeled "mixing curve") rather than the straight-line approximation commonly appearing in the literature whereby the two points on the saturation vapor curve are connected with a straight line along which it is assumed the mixing takes place. We show the derivation and computation of this curve in the

Appendix. As it happens, the approximation results in overestimates of the amount of liquid water which will condense.

Scorer has raised the possibility of a warm efflux carrying so much condensed water that the efflux has a density exceeding that of the ambient air (15, 16). We have computed, for illustration, that originally saturated air at 164° F when cooled to 130° F without losing its resulting liquid condensate would have a density equal to that of saturated ambient air at 47° F. However, this does not occur in a natural-draft cooling tower, those figures coming from an industrial drier installation. A cooling tower emitting saturated air at 131° F (55° C) into ambient saturated air at 50° F (10° C) will have its "apparent temperature"(per Blum, Ref. 2) follow the curve plotted on the graph appearing on the next page. (Detailed computation appears in the Appendix.) Then, the resulting condensation will releast latent heat so that only a fraction of the excess vapor at the mixture apparent temperature will condense visibly. This condensate will now, however, threaten precipitation if the excess appears in high concentration, even though the mixture of equal masses of saturated air at 55° C and 10° C will condense only about 4 g water per cubic meter of air and not approach the Scorer criterion for neutral buoyancy of the warm efflux by increased density from contained liquid. (It would require over 100 g liquid per m^3 to make the warm mixture at 35.1° C equal the density of ambient air at 10° C.)

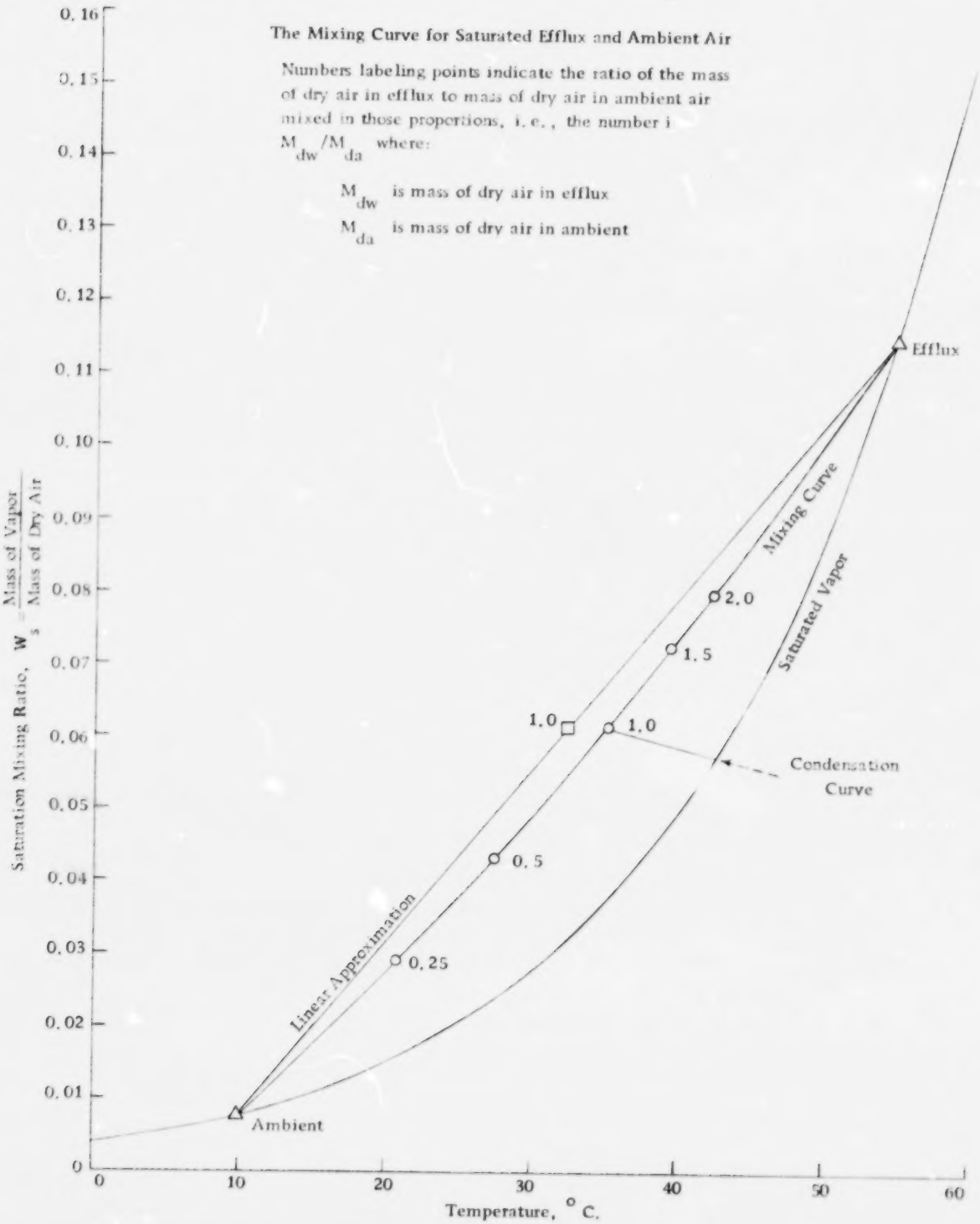
The condition visualized by Scorer requires heat loss by conduction or temperature drop by expansion. If conduction does not chill the humid air,

The Mixing Curve for Saturated Efflux and Ambient Air

Numbers labeling points indicate the ratio of the mass of dry air in efflux to mass of dry air in ambient air mixed in those proportions, i.e., the number i M_{dw}/M_{da} where:

M_{dw} is mass of dry air in efflux

M_{da} is mass of dry air in ambient



could expansion do this? Not at the low speeds of a natural-draft tower, some 5 ft/sec.

Pressure reduction because of velocity head, according to McKelvey and Brooke (11, p. 108), may amount to a typical pressure drop of 0. 2 inch of water for the air flowing upward through a natural-draft tower. This pressure drop of approximately 1 lb/ft^2 amounts to about 0. 05% of the atmospheric pressure of 14. 7 lb/in^2. The resulting expansion will cool the air only about 0. 1° F, condensing only about 1/3 g/m^3. Thus, again no condensation sufficient to overcome the warm efflux buoyancy appears to occur.

A visible efflux does have the possibility of a net loss of heat by radiation, but we estimate this at several orders of magnitude less than the rate needed to counteract the buoyancy of the efflux, assuming 55° C represents an upper limit of warm efflux temperatures.

Downwash (Fig. 1) might carry any visible plume down to levels below the efflux, but this seems unlikely to form a stagnant fog bank because of the wind required.

The possibility remains that a drizzle occurs from the plume and that this drizzle will evaporate as it falls into the surface air (Fig. 2). However, the conditions for such a drizzle from a plume are not known with certainty. The criterion of 0. 5 gram of liquid per cubic meter of air used by Blum (2) seems reasonable, but field verification does not appear in the literature. It might require so much time for the drizzle actually to form that normal dilution with ambient air will preclude much if any actual precipitation.

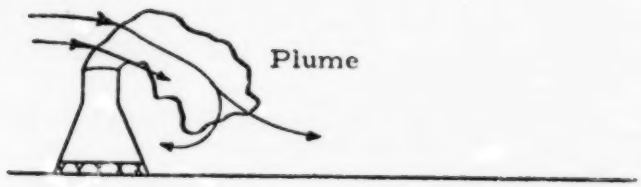


Figure 1. Downwash in the lee of a cooling tower can bring a plume toward the surface, but great heights of natural-draft units tend to offset possibilities of actually reaching the surface.

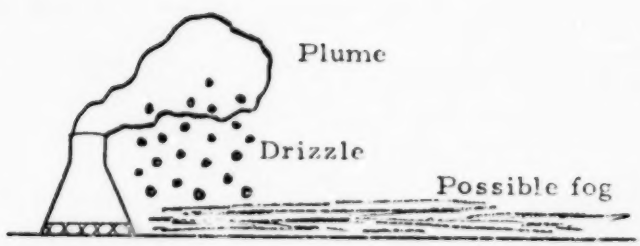


Figure 2. A drizzle may result from the rising of a dense plume, and subsequent evaporation of this precipitation into the chilled surface air can produce surface fog. Calculation requires information on the drizzle rate and its effectiveness in fog formation.

Therefore, a field investigation in the vicinity of a tower producing dense plumes should occur for the establishment of this point, especially with calm or very light winds so as to maximize the effects of a deep plume with slow dilution.

If a drizzle predictably occurs from a cooling tower plume, we could then make fairly positive computations of the fog production in surface layers which might be cooling at a rate approaching eventual natural fog which gets hastened by this enhanced vapor content together with the cooling effect of the evaporation. Quantitatively, however, this will depend upon the temperature of the falling droplets. the size and number of the drops, and the speed at which these drops fall downward. A proper evaluation of this effect will require more information than we have found on the effectiveness of a cooling tower in producing precipitation. The existing computations by Blum (2) and their use by McKelvey and Brooke (11) leave open such questions as the true "precipitation point".

AREA AFFECTED

If precipitation as described here should lead to a surface fog, how great an area will it affect? To answer this question, we must consider the wind and stability of the atmosphere as well as the terrain. The wind will distribute the plume horizontally, while the stability will dictate the turbulence and hence the vertical and lateral spreading of the plume. The terrain will determine the channeling effects on the surface fog.

While the equations presently accepted for atmospheric dispersion estimates have appeared in Turner's summary (17), the particular modifications adapting these ideas to the precipitation from a plume have probably their definition in the paper by Blum (2), from which the following concept particularly applies.

The mixing of ambient air with the saturated, warmer air will result in a mixture having excess vapor for the temperature of the mixture, and this results in some condensation. Meteorologists call this effect a "steam fog" when it occurs in the cold air passing over a warm body of water. However, in the efflux from a cooling tower we should expect the concentration of liquid droplets to exceed the rather modest liquid concentration likely to occur when cool air passes over open water. Blum adopted the criterion that when the air contains liquid droplets exceeding 0. 5 g/m^3, collisions will produce enough larger droplets to fall out as a drizzle. On a preceding page we show a saturation water vapor content curve on which a curve appears which represents the locus of various mixtures of ambient air to air saturated and in thermal equilibrium with water at an assumed temperature. Blum's 0. 5 g/m^3 criterion converts to a Δw_s value of 0. 00044 at ordinary sea level conditions. For the hypothetical case graphed earlier, this value gets exceeded for all mixtures exceeding 0. 5% cooling tower efflux in the final mixture. Therefore, it would appear to this writer that a drizzle should occur over practically the entire area of the plume. If so, we could predict that such an area would have a steady wetting from the drizzle and that the air near the surface would

also receive vapor from direct evaporation of the falling drizzle. Moreover, the smaller this area, the greater the amount of "precipitation" collected. From the standpoint of production of surface fog, this should mean that a smaller patch of fog will appear with the most stagnant air, which does not spread the plume out as much. On the other hand, the lowest intensities of precipitation will occur when a wind carries the plume over a great area as a slender streamer. In fact, this might assure that none of the drizzle would reach the ground and that the consequent dilution of the vapor would prevent the humidity in the surface air from ever reaching the high values needed to produce a fog. This emphasizes the very special factors required for fog production by this process of mixing-condensation-drizzle-evaporation process. It seems that fog, when it occurs in this process, will result most probably from the drizzle occurring in humid, stagnant air already quite close to the fog condition as a result of natural cooling. However, it remains to determine how readily a drizzle really will occur and also the ease with which fog will then form.

What equations to use will then depend upon three kinds of process which we can express mathematically, namely (a) the mixing of ambient air with humidified air to form a plume, (b) the air movement which distributes the plume-laden air, and (c) the formation of a surface fog in the natural air into which drizzle falls. Probabilities of occurrence would range downward from the highest probabilities (but not necessarily very high in absolute terms) at night with cooling surface temperatures, high humidity in the ambient air,

and calm winds. A cloud cover or the arrival of dawn would tend to cancel the chance of fog in the surface air, dry air would forbid fog as well, and brisk winds would reduce the drizzle intensity. Any one of these offsetting conditions could greatly reduce the chance of a fog, so we can estimate chances of fog formation from a cooling tower as quite low. Moreover, careful site selection should preclude the chance that a fog formed by the drizzle would ever create a liability.

SITE SELECTION

If a fog does form as a result of the drizzle from a plume, the result could still remain harmless if the site provides for the fog to drain away to unpopulated areas or get carried away in normally active air movement past the site. This puts a premium on locations such as that at the Chavalon Alp, where the fog can drain or get moved laterally because of the exposed location. This, however, assures that the cooling tower would have to withstand more wind than in a lower, sheltered location.

Before selecting a site, therefore, it appears essential to secure data on the extremes and normals of temperature, humidity, and wind in the various locations under consideration. Since such data in the precise location will seldom already exist, a year's sampling of weather data would have to be collected. Data need not be taken continuously but simply during periods judged to represent extreme or typical synoptic cases. Then, for the various weather types the analyst could determine the frequency of occurrence of the

type and use this as a probability figure in determining over-all probability from the product of the probability of fog forming in that particular case and the probability of that case occurring.

Downwash around buildings should occur at moderate wind speeds, but the exact conditions and the nature of the downwash will require wind tunnel studies of model structures for a given site complex. Moreover, downwash can occur as a spilling of air currents over a mountain ridge, for instance, so any such terrain feature upwind of a site can influence large-scale lee-wind effects. For study of such terrain effects a field study using tracer techniques would reveal the extent to which a proposed cooling tower efflux might get swept down into a valley when wind blows across elevated terrain upwind of such a tower.

The fact that modern cooling towers have apparently caused few complaints of fog except in downwash conditions would argue that this hazard has a low probability and that suitable sites greatly exceed in number the unfavorable sites which trap or concentrate the fog. It would appear relatively easy to select a favorable site for a natural-draft tower, and perhaps elevated sites for mechanical-draft towers would be nearly as easy to obtain.

CONCLUSIONS

Site selection based upon factual weather data can obviate foreseeable problems with fog caused by cooling towers or with the other effects of drizzle caused by towers, such as icing, etc. These effects will be minimum if

the drizzle falls into a relatively deep layer of air and thereby evaporates with great dilution by air. Thus, the natural-draft tower has an inherent advantage over the forced-draft tower because of the greater height of the efflux from the former. This advantage can perhaps be achieved in the case of a forced-draft tower by use of an elevated site so that the plume usually stands above still lower terrain sloping away from the cooling tower.

Objective determination of fog-forming probabilities as a result of suspected drizzle from cooling tower plumes will require field information about the actual drizzle intensities and the effectiveness of such drizzle in producing surface fog.

Empirical probabilities of high humidity and light air movement in combination with surface air cooling represent the chief source of information obtained from the estimate of the frequency of occurrence of fog nuisance created by the cooling towers. A further imposition of the probability of occurrence of sub-freezing temperatures would provide probabilities of occurrence of either icing or show which could adversely affect the activities nearby.

Site selection should consider finally the need for adequate clearance or a buffer zone of real estate to assure that the plume itself would not deposit a drizzle over terrain where the owners considered the precipitation a primary nuisance. In this case the calculated extent of the plume will depend upon the thermodynamic properties of the ambient air plus the extent of the dilution produced by natural turbulence exchanging the plume air with ambient air.

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APPENDIX

When parcels of warmed, humidified air mix with parcels of ambient air, the resulting mixture has a temperature and water vapor content which we can compute from calorimetry and the method of mixtures.

Assume mixing

$$M_{vm} + M_{dm} = M_{vw} + M_{dw} + M_{va} + M_{da}$$

Where:

M_{vm} = Mass of vapor in mixture

M_{dm} = Mass of air in mixture

M_{vw} = Mass of vapor in saturated parcels inside tower

M_{dw} = Mass of dry air in parcels saturated in tower

M_{va} = Mass of vapor with ambient dry air initially unaffected in tower

M_{da} = Mass of ambient dry air initially unaffected in tower

$$\therefore \quad M_{vm} = M_{vw} + M_{va}$$

$$M_{dm} = M_{dw} + M_{da}$$

But $M_{vw} = M'_{va} + M_e$

Where:

M'_{va} = Mass of vapor initially associated with air which gets saturated

M_e = Mass of vapor evaporated into parcels which get saturated

Heat Exchange:

$$(T_i - T_m)(M_{dw} c_{pd} + M_{vw} c_{pv}) =$$

$$(T_m - T_a)(M_{da} c_{pd} + M_{va} c_{pv})$$

Where:

T_i = Inlet temperature of water (hot)

T_a = Ambient air temperature

$$(T_m - T_a) = (T_i - T_m)\frac{M_{dw}(1+2w_w)c_{pd}}{M_{da}(1+2w_a)c_{pd}}$$

[since $c_{pv} \cong 2c_{pd}$]

c_{pd} = Specific heat of dry air at constant pressure

c_{pv} = Specific heat of water vapor at constant pressure

Where:

w_a = Ambient mixing ratio, M_{vw}/M_{da}

w_w = Saturated mixing ratio at T_i, M_{vw}/M_{dw}

T_m = Resulting temperature of mix prior to condensation, i.e., Blum's "apparent temperature".

$$T_m - T_a = (T_i - T_m)\frac{M_{dw}(1+2w_w)}{M_{da}(1+2w_a)}$$

$$\cong (T_i - T_m)\frac{M_{dw}}{M_{da}}(1-2w_a+2w_w) \quad [\text{Since } w_a < w_w \ll 1]$$

$$\cong (T_i - T_m)\frac{M_{dw}}{M_{da}}[1+2w_w] \quad [\text{If } w_w \gg w_a].$$

Vapor Mixture:

$$w_m = \frac{M_{vm}}{M_{dm}} = \frac{M_{vw}+M_{va}}{M_{dw}+M_{da}}$$

$$w_m = \frac{w_w M_{dw} + w_a M_{da}}{M_{dw}+M_{da}}$$

$$= w_w \frac{M_{dw}}{M_{dm}} + w_a \frac{M_{dm}-M_{dw}}{M_{dm}}$$

$$= w_w P + w_a(1-P)$$

Now, let

$$P = \frac{M_{dw}}{M_{dw}+M_{da}} = \frac{M_{dw}}{M_{dm}}$$

Now, $w_w \cong 0.136$ at T_i of 55°C or 131°F (Assume saturated efflux and ambient air.)

$w_a \cong 0.0076$ at T_a of 10°C or 50°F

$$\therefore \quad T_m - T_a = (T_i - T_m)\frac{M_{dw}}{M_{da}}[1.27]$$

Now, compute T_m for various values of the ratio M_{dw}/M_{da}. Results tabulated at right.

Results:

M_{dw}/M_{da}	T_m °C	w_m g/kg
0.25	20.8	29
0.5	27.5	43
1.00	35.1	61
1.50	39.6	72
2.00	42.4	79